Characterisation of the biosand filter for *E. coli* reductions from household drinking water under controlled laboratory and field use conditions

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Abstract More than a billion people in the developing world lack access to safe and reliable sources of drinking water. Point of use (POU) household water treatment technology allows people to improve the quality of their water by treating it in the home. One emerging POU technology is the biosand filter (BSF), a household-scale, intermittently operated slow sand filter. Laboratory and field studies examined *Escherichia coli* reductions achieved by the BSF. During two laboratory studies, mean *E. coli* reductions were 94% and they improved over the period of filter use, reaching a maximum of 99%. Field analysis conducted on 55 household filters near Bonao, Dominican Republic averaged *E. coli* reductions of 93%. *E. coli* reductions by the BSF in laboratory and field studies were less than those typically observed for traditional slow sand filters (SSFs), although as for SSFs microbial reductions improved over the period of filter use. Further study is needed to determine the factors contributing to microbial reductions in BSFs and why reductions are lower than those of conventional SSFs.

Keywords Drinking water; point of use; reduction; slow sand filtration; water treatment

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Introduction

Clean and typically safe drinking water is taken for granted in the developed world but its lack takes a heavy toll in terms of the waterborne disease burden, lost time and decreased productivity of more than a billion people in the developing world (Sobsey, 2002). For the majority, access to disease-free, piped drinking water is years or decades away. In the meantime, people must obtain their own drinking water wherever they can, often from contaminated, unsafe ground and surface water sources. Point-of-use (POU) water treatment and safe storage technologies at the household level offer an alternative to consuming untreated, unsafe water. The goal of household POU technology is to allow people who only have access to unsafe water sources to improve the quality of their water by treating it themselves, in their homes.

A number of different household POU technologies are available, including boiling, chlorination, solar (sunlight) disinfection, combined chemical treatments for coagulation, flocculation, settling and disinfection and various filtration methods. One of the most promising emerging POU filtration technologies is the biosand filter (BSF), a household-scale, intermittently operated slow sand filter. Although the ability of traditional slow sand filters to reduce pathogens in water is well-documented, the effectiveness of the BSF unit is uncertain because it has different design and operating properties. Traditional slow sand filters are operated continuously at constant head and flow rate and the upper layer of sand is periodically replaced. However, the BSF is operated intermittently, head and flow rate vary and the upper few centimetres of sand containing the schmutzdecke

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are not replaced but rather cleaned periodically by agitation and decanting of the released contaminants and excess biological growth.

Only limited evidence of the biosand filter's ability to reduce waterborne microbes in laboratory studies or field use has appeared in the peer-reviewed literature. Palmateer *et al.* (1999) documented >99% removal of *Giardia* cysts and *Cryptosporidium* oocysts and 65–90% reductions of indigenous faecal coliform bacteria. Buzunis (1995) reported typical faecal coliform reductions of about 96% in laboratory studies. To date, no studies have been published on removals of *Escherichia coli* by the BSF in either laboratory or field studies. As *E. coli* is the recommended faecal bacterial indicator of drinking water quality, and is less prone to variability and uncertainty caused by the diversity of faecal coliform bacteria, studies on its reduction by the BSF are much needed. The objectives of the current study were to measure *E. coli* reductions under controlled laboratory dosing studies and under actual field-use conditions in the Dominican Republic and to compare results achieved in the laboratory with those results obtained in household use of the BSF in the field.

Methods

Laboratory filter preparation

Plastic filter units with 60 L capacity were obtained from Davnor Water Treatment Technologies Ltd., Alberta, Canada. Crushed granite gravel was purchased locally and sieved through three mesh screens to prepare the filter media of the appropriate size (mean diameter of ≤1 mm) in accordance with field practice and to provide an initial flow rate of 0.7–1.1 L/min. Filters were loaded with 5 cm of underdrain gravel, 5 cm of medium size gravel and 40 cm of sand (Figure 1). During loading, the empirical pore-volume of the filters was measured by loading the filter to saturation. After loading the filter, the initial flow rate was measured by filling the upper filter chamber full and measuring the time it took to filter 500 mL.

Longitudinal, constant dosing, filtration experiments

Two constant dose filtration experiments were conducted. In the first experiment, a filter was dosed for 17 d with 40 L/day lake water seeded with 10^5 CFU/mL *E. coli* B. In the second experiment, a filter was dosed daily for 43 d with lake water seeded with

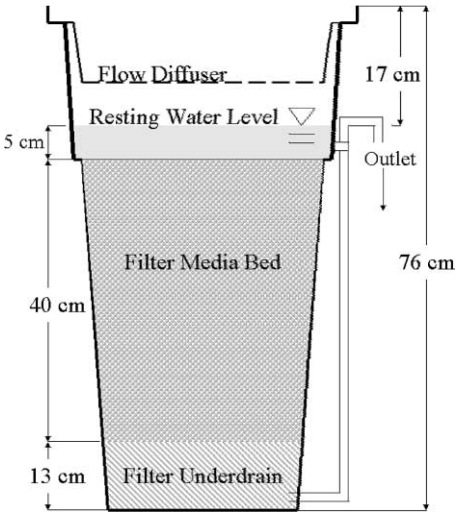

Figure 1 A cross-sectional view of the plastic biosand filter

10^3 CFU/mL *E. coli* B. In both experiments, raw influent surface water was collected from the local drinking water treatment plant (Orange Water and Sewer Authority, Orange County, NC, USA) at weekly intervals in 10 L cubitainers (Yankee Containers, New Haven, CT, USA) and stored at 4 °C until 1 d prior to dosing. Then, 40 L of water was allowed to come to room temperature (approximately 25 °C) prior to dosing onto the filters. For both runs, the filters were dosed daily with 40 L of water that was seeded to a target initial concentration of *E. coli*.

E. coli and filter dosing

A pure culture of *E. coli* strain B (ATCC No. 11303) was grown to log phase in shaker culture flasks of tryptic soy broth at 36 °C (EPA Method 1602; EPA, 2001). After reaching log phase, the culture was cooled to approximately 4 °C, serially diluted in PBS and spread plated onto MacConkey agar (Becton-Dickinson, Franklin Lakes, NJ, USA). Plates were incubated at 37 °C (24 h) and resulting colonies were counted to express the *E. coli* concentration as CFU/mL. Log-phase cultures were stored for up to 7 d at 4 °C and maintained stable concentrations of viable *E. coli*. Cultures were prepared weekly as needed during the two dosing experiments. For daily dosing, the culture was serially diluted in lake water immediately prior to seeding to prepare a stock suspension and this stock was dosed into lake water to achieve the desired *E. coli* concentration in water to be dosed into the filter.

Water analysis methods

E. coli was sampled and assayed in composite influent water samples from 40 L, daily doses, composite filtered water samples (from the first 30 L of filtered water) and samples of the seeded influent water from the day prior to sampling. This seeded influent sample was stored next to the filter overnight to simulate temperature conditions in the filter. In both experiments these composite samples for *E. coli* analysis were taken on day 0 and then at approximately weekly intervals throughout the length of the challenge study. To examine the effect of retention time of water in the filter on microbial reduction, a composite of the first 15 L of filtered water (which is water that was retained in the filter bed from the dose of seeded influent water of the preceding day) was sampled and analysed on days 42 and 43 of experiment 2. Log_{10} reductions of *E. coli* were calculated as $\log_{10}$ influent water concentration minus $\log_{10}$ filtered water concentration. *E. coli* concentrations in water were quantified via membrane filtration on MI agar BBL™ (Becton-Dickinson) using EPA Method 1604 (EPA, 2002). Turbidity and pH were measured using a turbidimeter (Model 2100N, Hach, Loveland, CO, USA) and pH meter (Model 215, Denver Instruments, Denver, CO, USA).

Field sampling

Fifty-five households that had purchased biosand filters in 2004 and were living in a village on the outskirts of the city of Bonao, Dominican Republic were each visited once between April and August 2005. All filters were fabricated and installed by local filter manufacturers who also initially trained an adult household member in filter use and maintenance. For each household visited, 250 mL samples of household water were taken prior to filtration and also directly from the filter outlet during filtration to avoid post-filtration contamination. Water samples were collected in 500 mL sterile Whirl-Pak® bags (M-Tech, Cheshire, UK), stored on ice, transported to the laboratory and processed immediately for pH, turbidity and *E. coli*. Samples were analysed for *E. coli* using the Colilert® biochemically based (defined substrate) culture assay system (IDEXX, Westbrook, ME, USA). Turbidity and pH were analysed using a 2100P portable turbidimeter

(Hach) and portable pH meter (Hach). Again, *E. coli* reductions were calculated as $\log_{10}$ MPN/100 mL influent water concentration minus $\log_{10}$ MPN/100 mL of filtered water concentration.

Results

Filter flow rate

The flow rates of filters over the course of the filter runs of the two laboratory experiments are summarised in Figure 2. During both experiments, the filter flow rates declined dramatically over time. The initial flow rate during experiment 1 was 0.67 L/min and by day 17 had declined to 0.09 L/min. Experiment 2 began with an initial filter flow rate of 0.9 L/min but it had declined to 0.2 L/min by day 25. In both cases, the filter flow rate declined to less than 25% of the initial rate. In both experiments, the empirical pore volume of the filter medium was determined to be approximately 18 L based on chemical tracer studies with dosed water containing added NaCl (data not shown).

E. coli reduction

In laboratory experiments 1 and 2 geometric mean reductions of *E. coli* by the biosand filter were 97 and 91%, respectively. In both experiments, the lowest *E. coli* reductions were found during initial days of filter dosing. The minimum *E. coli* reduction in experiment 1 was 1.2 $\log_{10}$ (93%) measured on day 4 and in experiment 2 it was 0.43 $\log_{10}$ (or 63%) on day 3. Maximum *E. coli* reductions were typically reached towards the end of the longitudinal filter dosing experiments. Maximum *E. coli* reduction in experiment 1 was nearly 2.0 $\log_{10}$ (or 99%), reached on day 17, and maximum reduction in experiment 2 was 1.9 $\log_{10}$ (or 98.9%), reached on day 42. The improvement in *E. coli* reductions during the length of the filter run is shown in Figure 3 for experiment 2. Table 1 shows the $\log_{10}$ *E. coli* reductions in two 15 L composite samples of initial filtrate from a daily water dose of 40 L taken on days 42 and 43 of experiment 2. *E. coli* reduction was approximately 0.3 $\log_{10}$ higher in the 15 L composite samples when compared with 30 L composite samples taken the same day (Table 1).

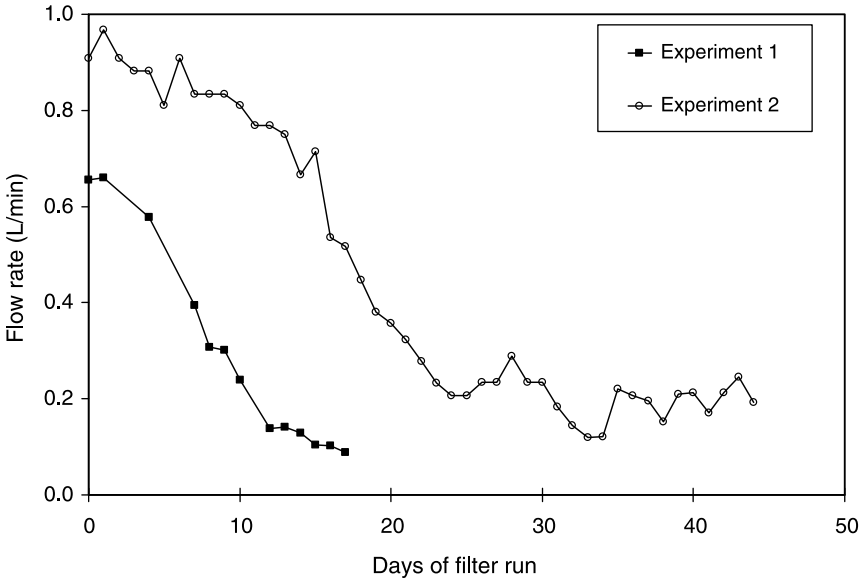

Figure 2 Flow rate of BSFs over time for laboratory experiments

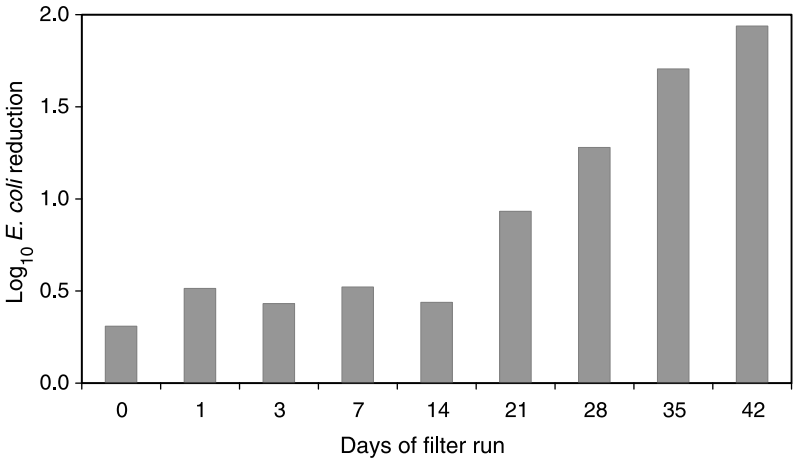

Figure 3 *E. coli* $\log_{10}$ reductions by BSF over time for laboratory experiment 2

E. coli reduction in the field

Data on *E. coli* reductions by household BSFs in the field are summarised in Table 2 and Figure 4. All households sampled had been utilising the BSF for periods of 4–11 months. Household waters prior to filtration were highly variable in concentrations of *E. coli*, pH and turbidity. Overall, filtered waters had lower concentrations of *E. coli*, lower turbidity and higher pH than pre-filter source waters (Table 2).

Filter performance varied greatly among the households in the field (Figure 4). The effectiveness ranged from filters that provided apparently no *E. coli* reduction to those that achieved a maximum reduction of 2.5-$\log_{10}$ (MPN) or 99.7%. On average, filters provided a 1.15-$\log_{10}$ (93%) reduction of *E. coli*. As shown in Figure 4, the observed *E. coli* reductions by household BSFs appeared to be approximately normally distributed, based on the normal distribution curve overlaid on the actual categorical $\log_{10}$ reduction data.

Discussion

There was wide variation in *E. coli* removals by BSFs both in the laboratory (range 63–99%) and in household use in the field (range 0–99.7%). The considerable variation in filter performance may have been dependent on such factors as the extent or stage of filter ripening (biological maturation) and filter use conditions with respect to water dosing, such as frequency of dosings and water volume/dose. The laboratory results suggested that some form of filter maturation occurred over the period of filter use, as evidenced in both experiments by flow rate reductions and increased bacterial removal efficiency over the length of the experiments (Figures 2 and 3). While filter maturation is a known essential component of slow sand filters, the bacteria removals of the BSF were considerably less than those previously observed for a typical SSF (>99%) (Hendricks and Bellamy, 1991). These findings suggested that further studies of microbial

Table 1 Effect of volume filtered on *E. coli* reduction by BSF in laboratory experiment 2

Volume filtered	*E. coli* d42	*E. coli* d43
15-L composite $\log_{10}$ reduction (% removal)	2.2 (99.4)	2.0 (98.9)
30-L composite $\log_{10}$ reduction (% removal)	1.9 (98.8)	1.7 (97.8)

Table 2 pH, turbidity and *E. coli* levels in raw and BSF filter waters in the field

Parameter	Before filtration	After filtration
Mean pH ($n = 47$)	7.4	8.0
Mean turbidity (NTU) ($n = 47$)	8.1	1.3
Mean $\log_{10}$ *E. coli* MPN/100 mL ($n = 55$)	1.7	0.6

removals and the development of functional biological activity in the BSF were necessary to determine the basis of the performance differences between conventional SSF and the BSF.

The lower concentrations, and hence greater removals of *E. coli* in the first 15 L of filtered water from a 40 L daily dose, suggested the potential importance of retention time in the filter bed to enhance microbial removals. Because the empirical pore volume was approximately 18 L, the initial 15 L were likely to have been residing in the filter during the period in between dosings. Therefore, this initial 15 L of filtrate had the longest period of contact with the filter bed and exposure to the biological activity within it. It is hypothesised that biological activity contributed to microbial reductions. However, these processes deserve more investigation as they appeared to have important implications for filter use and management practices.

Results from field sampling of filters in households suggested wide variations in bacterial removals in typical field use. However, field conditions of filter use can vary considerably from laboratory-controlled studies. Field samples of filtered water were 250 mL grab samples not composite samples of the filtered water. Source water quality, including *E. coli* concentration, was highly variable during the field sampling study. Consequently, it was impossible to determine if the range of variability of *E. coli* reductions was influenced by variable source water quality or actual differences in filter performance without more thorough examination of the household filters in the field. For example, differences in rate of maturation in the field installations and in the controlled laboratory studies could have explained differences in *E. coli* removals. Additional data, such as time since last cleaning of the filter, filter flow rate, filter dosing characteristics (i.e. frequency and volume of filter dosings), and the variability of source water quality, are needed to characterise and understand filter performance better in the field. Such detailed field studies, as well as more comprehensive and systematic laboratory studies, are in progress and will be subsequently reported.

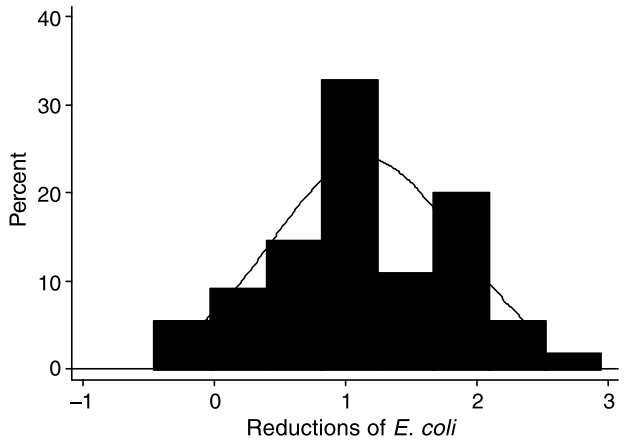

Figure 4 *E. coli* $\log_{10}$ reductions for biosand filters in communities surrounding Bonao, Dominican Republic

Conclusions

The results from laboratory experiments in which typical household BSFs were dosed with 40 L of water/day gave average *E. coli* reductions of 94%. However, *E. coli* reductions ranged from a maximum 98–99% in ripened (biologically mature) filters to as low as 63% for initial removals in unripened filters. Results from field sampling of filters in typical household use in the Dominican Republic also produced great differences in *E. coli* reductions, ranging from 0 to 99.7% (averaging 93% overall). The variability of BSF performance in reducing *E. coli* concentrations may have been due to such factors as the extent of filter ripening (biological maturation), how the filter was dosed with water (e.g. dose volumes and frequency of dosing) and the length of time the dosed water resided in the filter media before appearing as the filtrate. Further studies are needed to determine better the factors contributing to the variability of bacterial reductions by BSF as this could aid in identifying design features and operating conditions for optimised performance. Additional studies are needed to determine the extent to which these filters reduce waterborne bacterial (e.g. *Vibrio cholerae* and *Campylobacter*) and human enteric viral pathogens together with their ability to reduce household waterborne disease.

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